EXPERIENCE WITH THE DOD FLEET OF 30 FUEL CELL GENERATORS

L'EXPERIENCE AVEC LA FLOTTE DE DOD DE 30 GENERATEURS DE CELLULE DE CARBURANT

M.J. Binder, W.R. Taylor, and F.H. Holcomb
U.S. Army Engineer Research and Development Center, USA

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ABSTRACT

The U.S. Department of Defense has been operating a fleet of 200 kW Phosphoric Acid Fuel Cell power plants at 30 sites in the U.S. Eleven power plants began operation more than five years ago. The remaining 19 power plants were installed in 1997. The fleet has logged more than a half million operating hours. Several individual power plants have more than 30,000 operating hours and have started consideration for end-of-life types of issues: degradation rate, estimation of economic end-of-life, refurbishment/replacement/removal options, etc. Fleet-wide performance data, including system efficiency, availability, and outages, are presented. An analysis has been performed of cell stack voltage degradation, and subsequently used for an assessment of life expectancy of operating fuel cell power plants. End-of-life issues facing Department of Defense facility managers are discussed.

RESUME

Les Etats - Unis. Le service de Défense opère une flotte de 200 pouvoir de Cellule de Carburant d'Acide de Phosphoric de kW plante à 30 sites dans les Etats - Unis. Onze pouvoir plante a commencé l'opération plus qu'il y a cinq ans. Le rester 19 pouvoir plante a été installé dans 1997. La flotte a noté plus qu'un demi million opère des heures. Plusieurs pouvoir d'individu plante a plus que 30,000 opèrent des heures et ont commencé la considération pour la fin-de-les types de vie de questions: le taux de degradation, le jugement de fin économique-de-la vie, refurbishment/le remplacement/les options d'enlèvement, etc. Flotte-large exécution, inclut système, disponibilité, et interruptions de courant, sont présenté. Une analyse a été exécutée de cellule empile degradation de tension, et a utilisé par la suite pour une évaluation d'espérance de vie d'opère le pouvoir de cellule de carburant plante. La fin-de-les questions de vie font face au Service de directeurs de facilité de Défense est discuté.

INTRODUCTION

The United States Department of Defense (DoD), like many other large utility customers, is constantly concerned about the supply of reliable, cost-effective, electric power with minimal environmental impact. Distributed generation equipment such as fuel cell power plants have the potential for meeting these requirements. The arrival to the marketplace in 1992 of the ONSI PC25 Phosphoric Acid Fuel Cell (PAFC) power plant, the first fuel cell power plant to become commercially available, provided the DoD with the opportunity to evaluate this advanced technology as a possible replacement for outdated existing equipment on military facilities.

The FY 1993 and FY 1994 Defense Appropriations Acts provided $18M and $18.75M, respectively, worth of equipment procurement funds for the purchase and installation of natural gas fuel cells at DoD installations. The U.S. Army Engineer Research and Development Center's Construction Engineering Research Laboratory (USAERDC/CERL) was requested to manage this fuel cell demonstration program for the DoD. Thirty ONSI PC25 PAFC power plants (1-Model PC25A, 14-Model PC25B, and 15-Model PC25C) were purchased and installed at DoD demonstration sites through this program. These power plants were purchased as part of a turnkey package which included the power plant itself, engineering design, installation of the power plant, training in the operation and maintenance of the power plant for DoD site personnel, a diagnostic/remote monitoring computer for DoD site personnel, and sixty months of prepaid scheduled and unscheduled maintenance of the power plant. The sixty months of maintenance included all components of the PAFC power plant except the cell stack, which was limited to a one-year warranty. In addition, the purchase contract for the eleven Model PC25B power plants purchased as part of the FY 1993 Appropriation included an option for removal of the power plant and restoration of the installation site at the conclusion of the sixty-month maintenance period. The overall goals of this demonstration program were to increase production and thereby reduce the cost of PAFC power plants through economies of scale, and to provide a thorough evaluation of fuel cell performance over a wide range of conditions.

SELECTION OF DEMONSTRATION SITES

The only restriction placed on the selection of the demonstration sites for the thirty PAFC power plants was that no power plant would be placed at a site at which the relative difference between electricity and natural gas costs was such that the use of a fuel cell to generate electricity would result in an electric energy cost in excess of that of the existing electricity purchase cost. Beyond that restriction, sites were selected to provide the greatest diversity of site conditions as possible. Selection of these sites was based on a combination of various criteria including interest of site personnel, energy cost savings, diversity of electrical and thermal applications, geographic region and climatic diversity, site physical considerations, and environmental considerations.

Site Selection Criteria

The most important criterion for site selection was the interest and enthusiasm of site personnel. This was considered critical in order to expedite the installation process and to provide continued support through the demonstration period. Potential energy savings, based on electric energy savings as well as natural gas savings through recovery of the by-product thermal energy, was the next most important criterion. These two criteria formed the list of potential candidate installation sites and determined the initial relative ranking of these sites.

This list was then subjected to screening based on site physical considerations. These considerations included the availability of natural gas, the lengths of gas, electrical and thermal connections required, physical space limitations, etc. The final list of installation sites was then determined in such a way as to obtain the most diverse demonstration program as feasibility allowed.

As the base electrical load at each of the candidate sites was in excess of the 200 kW produced by the fuel cell, each fuel cell was configured to operate in parallel with the utility grid, making the specific electrical application of minor importance. Ten of the installation sites were configured with a backup power option, which allowed the fuel cell to support a dedicated electric load in the event of the loss of utility grid power.

Considerable diversity was obtained for the by-product thermal energy recovery applications. Eleven of the sites use the thermal energy to preheat makeup water at central heat plants. Three of the sites use the thermal energy for preheating makeup water and for domestic hot water at hospital utility plants. It is also used for heating both an indoor and an outdoor swimming pool. One site uses the thermal energy to run an absorption chiller, while another site uses it as the heat source for an industrial evaporator process. The thermal energy is also used for domestic hot water in a barracks, a dining facility, a laundry, a National Guard armory, a launch control facility, and an office building.

Sites were chosen to provide a range of geographic location and climatic conditions. Selected sites ranged from very hot to very cold temperatures, from very arid to very humid conditions, and from sea level to over 1600 meters in altitude. As the original language of the Congressional appropriations recommended that some of the fuel cells in this program be placed in areas in need of enhanced air quality, several sites were selected that were in air quality non-attainment areas.

Site Selection Process

Initial candidate sites were identified by Army, Air Force, and Navy/Marine Corps Headquarters by soliciting their respective Major Commands or Major Claimants. As awareness of the process grew, individual installations requested to become a part of this program. This insured the interest and enthusiasm of installation personnel at these candidate sites. Initial screening of candidate sites was performed through an economic analysis based on total electricity and natural gas usage and average unit costs as provided by the Defense Energy Information System (DEIS). This economic analysis considered the electrical savings available through operation of a fuel cell power plant, the associated natural gas costs to operate the system, and the natural gas savings obtainable through recovery of the by-product thermal energy.

Installations that appeared to be good potential candidates as a result of this initial screening were then asked to submit copies of their actual past utility bills for a 12-month period so that the economic analysis could be refined by using actual monthly energy consumption and utility rate schedule data. In addition, each candidate installation was asked to provide information regarding the degree of air quality attainment for the region in which they were located, as well as a description of the intended application for the recovered by-product thermal energy and an estimate of the amount of this recovered thermal energy that they could use.

Site visits were made to those installations that still appeared to be good potential candidate sites at the end of this initial evaluation. These site visits allowed for refinement of the estimate of the by-product thermal energy usage, an analysis of the logistical factors surrounding potential fuel cell installation (e.g., distance from gas line, lengths of pipe and wiring runs, availability of sufficient land space to site the fuel cell, etc.), and the development of a conceptual design package. The successful candidate sites were then identified to the ONSI Corporation to be selected installation sites through individual contract modifications. A map depicting the locations of the fuel cell demonstration sites is given in Figure 1.

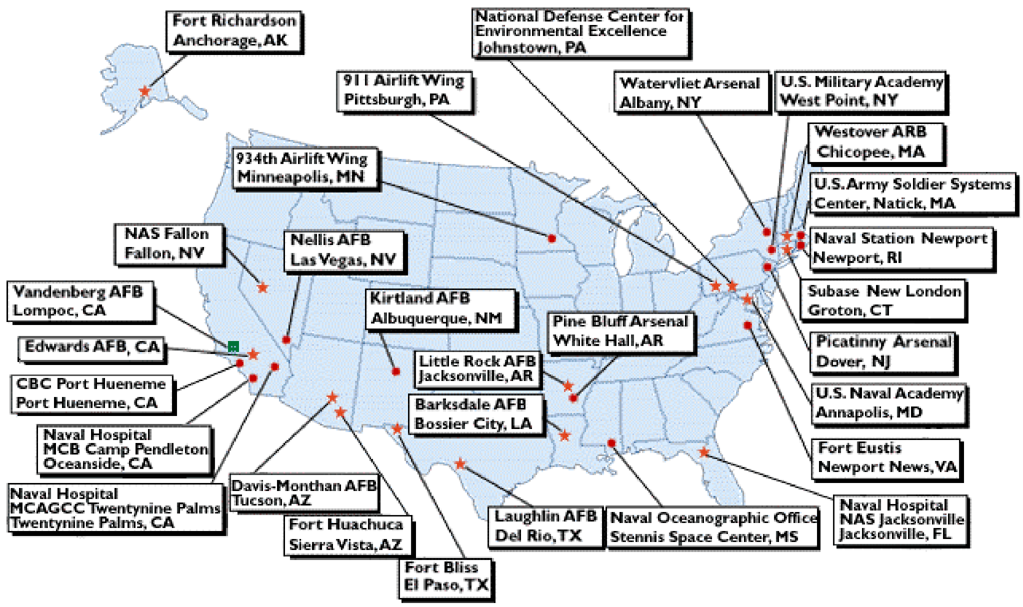

Figure 1. DoD Fuel Cell Sites.

A Kickoff Meeting was held on site shortly after each contract modification to initiate the design and installation process. The site Point of Contact was requested to assure that all site personnel who would need to be involved in any way with approval of the fuel cell project would be in attendance at this meeting to voice any concerns or requirements that they might have. This allowed the installation process to proceed in as smooth a manner as possible. When ONSI completed their installation design, a Design Review Meeting was held on site. Once the design met with the approval of all pertinent individuals, the installation process began. When the fuel cell was installed, ONSI then subjected it to an Acceptance Test. The parameters tested and the range of acceptable values had been previously determined and made a part of the fuel cell purchase contractual agreement. ONSI subsequently prepared an Acceptance Test Report incorporating the results of the Acceptance Test, and presented it to site and USAERDC/CERL personnel at an on-site Acceptance Test Meeting. At that point ownership of the fuel cell power plant was transferred to the site. In most cases, a Dedication Ceremony was held at the site some time after the Acceptance Test Meeting to publicize the site's participation in the demonstration program.

FUEL CELL FLEET PERFORMANCE

USAERDC/CERL personnel have been monitoring the operational performance of each of the fuel cell power plants in the DoD fleet. This includes total operating hours, total electricity production, total by-product heat recovery (PC25B sites), cell voltage degradation, availability, efficiency, estimated energy cost savings, air emissions, and forced outages. The lone Model PC25A fuel cell power plant, installed at Vandenberg Air Force Base, CA, was shut down by site personnel after only 2500 operating hours. The decision to shut this power plant down prematurely was based on site-specific conditions unrelated to the performance of the power plant. For this reason, only the Model PC25B and PC25C power plants are included in the analysis that follows.

Operating Hours/Availability

As of September 1, 2000, the DoD fuel cell fleet had logged more than 614,000 operating hours. The lifelong average unadjusted availability for the Model PC25B fleet was 56%, while that for the Model PC25C fleet was 77%. Individual Model PC25B fuel cell power plant availabilities ranged from 30% to 75%, while individual Model PC25C availabilities ranged from 62% to 82%. In the three-month period preceding September 1, 2000, the Model PC25C fleet unadjusted availability was 87%. In calculating unadjusted availabilities, a power plant is considered to be unavailable at any time it is not producing net electrical output power, regardless of the reason. For this reason, times for which the fuel cell is not available, for reasons not directly attributable to the fuel cell itself, are included in the calculations. Examples of these types of time periods include scheduled maintenance activities, shutdown of the natural gas supply to allow maintenance of the natural gas pipeline system, the necessity to shut the electrical output power down to allow for safe maintenance of the utility grid, etc. If these types of unavailable time periods were to be accounted for, the resulting adjusted availabilities would be much higher than the unadjusted values quoted above. Efforts are currently underway to account for these time periods in the determination of availabilities.

Several of the Model PC25B power plants showed signs of excessive stack voltage degradation within a few months of startup. As a result, ONSI shut down the entire PC25B fleet until it could determine the cause of these problems. It was later determined that all of the power plants that were experiencing this problem were located in hot desert regions. Under these conditions, the fuel cell requires considerable makeup water. This water was determined to come from ground sources that were high in silica content. This led to clogging of the stack cooling channels resulting in the degradation of the stacks. Fuel cells installed under these conditions are provided now with an extra resin bottle and a reverse osmosis unit to counteract this effect. With the introduction of the Model PC25C power plant, ONSI made the decision to no longer support the Model PC25B power plants. This led to the unavailability of parts, particularly inverter parts, as these power plants aged, thus contributing to the unavailability of these units. In all, five Model PC25B fuel cell stacks were replaced, one stack was renovated, and one stack failed without a replacement being available. To date, two of the sites have elected to exercise their option to have their power plants removed and the installation site restored. It is anticipated that all of the remaining Model PC25B sites will eventually exercise this option as stacks fail, needed parts become unavailable, or efficiency drops to the point that further operation becomes economically unfeasible.

The Model PC25C fuel cell power plant featured a high-grade heat recovery option, which allowed for heat recovery at a higher temperature than that associated with the Model PC25B. The heat exchangers used to accomplish this failed frequently in the initial units. This led eventually to a redesign by ONSI, and subsequent retrofit of all Model PC25C power plants supplied with this option. The new design has been successful, but the previous design led to significant down time that negatively affected fleet availability. Five Model PC25C fuel cell stacks have been replaced. Two of these were due to foreign matter inadvertently introduced in the stack cooling channels during the manufacturing process. The other three were replaced due to a failure to be able to sustain rated electric output power. One entire power plant that inadvertently shut down during the cold of winter and froze, had to be completely rebuilt. Lessons learned from the Model PC25B fleet, and from the early units in the Model PC25C fleet, led to several retrofits found in the current version of the PC25C, resulting in the significant increase in availability seen in the recent three month availability value given earlier.

Outages

One measure of fuel cell performance is the average number of operating hours between events that cause the fuel cell to shut down; i.e. Mean Time Between Forced Outage (MTBFO). For the Model PC25B fleet over its entire operating life, MTBFO is approximately 1594 hours. Similarly, for the Model PC25C fleet, MTBFO is 1766 hours. For the most recent 12-month period, MTBFO for the Model PC25C fleet improved to 2621 hours.

Another aspect of outages (which can also directly affect availability levels) is the average length of time that the power plant stays down after an outage has occurred. For the Model PC25B fleet, the average duration of a forced outage has been approximately 899 hours. For the Model PC25C fleet, average duration of an outage has been 317 hours. For the Model PC25C fleet over the most recent 12-month period, average duration of a forced outage has been about 804 hours. The increase in duration of a forced outage for the most recent 12-month period for the Model PC25C fleet is attributable almost entirely to the power plant that froze in winter as mentioned earlier. For some reason, ONSI took over two years to bring this power plant back on line

A variety of causes have contributed to the quantity of forced outages. If causes are grouped by power plant subsystem for the Model PC25C power plants, the two groups contributing to the largest number of outages are the Miscellaneous Electrical group and Thermal Management System group. Miscellaneous Electrical includes inverters, PC cards, fuses, pole and bridge failures, power supplies, relays, controllers, circuit breakers and grid disturbances. Miscellaneous Electrical was responsible for more than 60 occurrences over a 2.5-year period in the life of the Model PC25C fleet. If causes for the Model PC25C fleet outages are listed by the specific component, the majority of occurrences are related to inverters and bridges. In the most recent 12-month period, inverter problems have continued to be a major contributor to outages.

Efficiency

Following the initial installation, each power plant was required to demonstrate, as part of the Acceptance Test, the capability to provide rated power (200 kW) at the rated natural gas input flow rate (53.8 m^3/h +/- 2.83 m^3/h). Using values of energy content for natural gas based on an average of ten sites, this corresponds to an initial electrical energy conversion efficiency of 39% +/- 2% (LHV) and 35% +/- 2% (HHV). Individual unit average electrical efficiencies over the entire operating life to date ranged from 33% to 40% for the Model PC25B fleet, and from 31% to 40% for the Model PC25C fleet. Individual unit average overall (electrical energy plus by-product thermal energy recovered) efficiencies ranged from 39% to 82% for the Model PC25B fleet. Also, at several sites, fuel cell power plant thermal output has been observed to routinely be greater than the manufacturer's nominal output rating (2.05×10^5 W/h), especially during winter months. The Model PC25C power plants were not supplied by ONSI with internal instrumentation to monitor by-product heat recovery, as the Model PC25B power plants had been, so no data is available at this time to categorize by-product heat recovery from these units. These power plants have been subsequently equipped with external heat recovery sensors and are in the process of being retrofitted to allow for remote data monitoring, which will allow for analysis of heat recovery from these units.

Cell Stack Voltage

As PAFC power plants age, the phosphoric acid electrolyte in the cell stack becomes depleted. This results in a reduction in the cell stack voltage, requiring an increase in fuel flow rate to maintain a given net electrical output power. Cell stack voltage can be, therefore a potential indicator of the cell stack life remaining. Variation of fleet average cell stack voltage as a function of cell stack load time is shown in Figure 2 for the Model PC25B fleet, and in Figure 3 for the Model PC25C fleet. As can be seen from these figures, the Model PC25B fleet exhibited a voltage decrease of 7.6% per 10,000 hours, while the Model PC25C fleet exhibited a voltage decrease of 5.04% per 10,000 hours.

The use of cell stack voltage as an end of economic life indicator can be somewhat misleading. For a given net output electrical power, cell stack voltage decreases approximately linearly with time. However, once the cell stack voltage drops to some limiting value (dependent on fuel cell model), it becomes no longer capable of driving the power inverter system. When this happens, the net output power of the fuel cell power plant must be rolled back. This causes the cell stack voltage to rise instantaneously, and begin a linear decay anew. Theoretically, this output power roll back process can continue to the point to which the fuel cell becomes incapable of even generating sufficient power for its own parasitic loads, although an economic feasibility limitation will certainly occur well before that time. Therefore, plots of cell stack power as a function of load time tend to mask the electrolyte depletion effect because of these voltage increases that accompany output power variations.

The overall effect of fuel cell stack electrolyte depletion is to increase the fuel flow rate required for any given net output electrical power. Perhaps a better indicator of economic end of life considerations can be obtained by looking at the variation of instantaneous electrical output efficiency with load time. This is obtained from the ratio of the electrical energy produced to the gas input, taken over a short time span, at any given load time. This variation is given in Figure 4 for the Model PC25B fleet, and in Figure 5 for the Model PC25C fleet.

As can be seen from the figures, the instantaneous electrical output efficiency decreases with time at the rate of 2% per 10,000 hours for the Model PC25B fleet, and at the rate of 0.8% per 10,000 hours for the Model PC25C fleet. These values can be used, along with local electric and gas utility rates, to determine the fuel cell cost of generating a unit of electrical energy. When factored in with scheduled maintenance cost (currently at around $18,000 per year), this can give an indication of when it makes economical sense to replace the fuel cell stack.

It should be noted that as the electrical conversion efficiency decreases, the recoverable by-product thermal energy actually increases. This can play a role in determining economic feasibility in cases for which this recoverable by-product heat has an economic value on a par with the electrical energy produced. This can occur in cases where the recovered by-product thermal energy is used to displace purchased electrical energy, as in the case of an absorption chiller, or where it displaces heat purchased through a district heating system (common in many parts of Europe). In the latter case, the purchase price of a unit of heat can be equivalent to the unit price of purchased electricity.

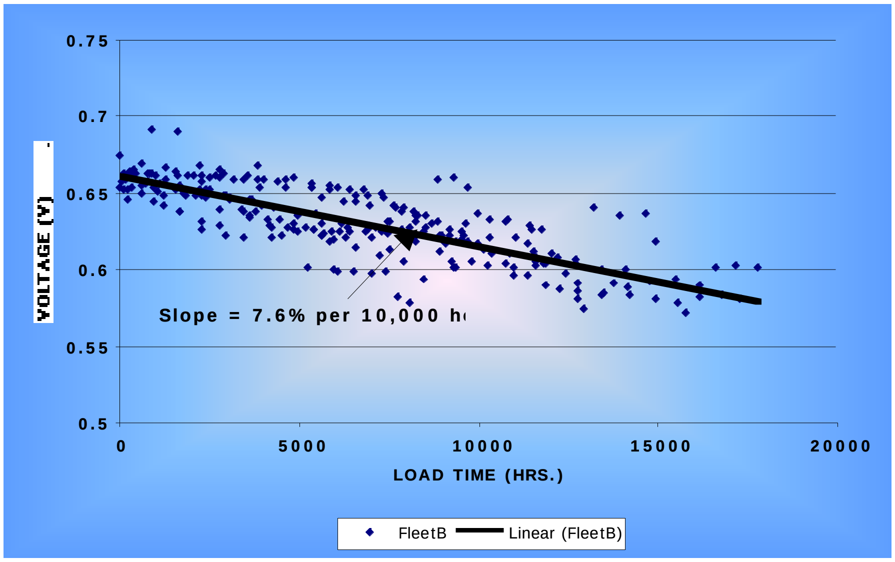

Figure 2. Average Cell Stack Voltage – Model PC25B Fleet

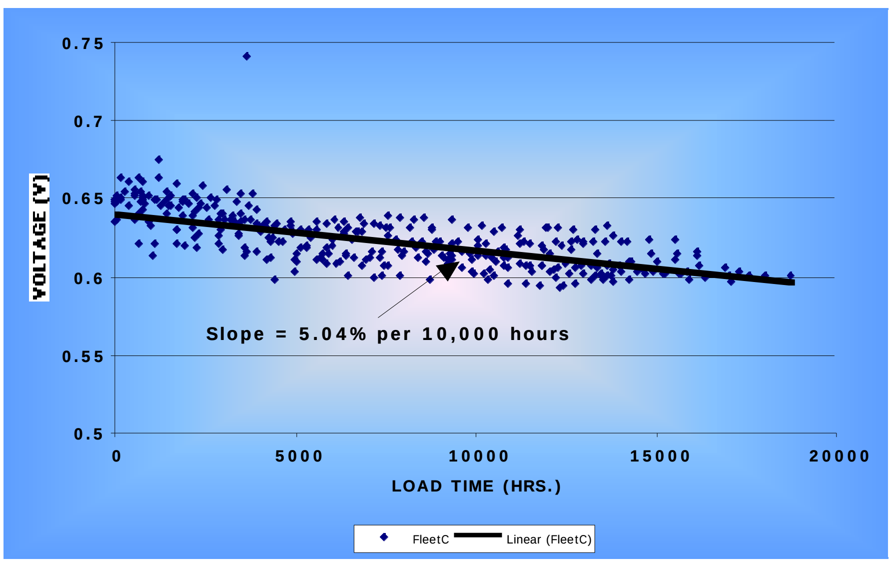

Figure 3. Average Cell Stack Voltage – Model PC25C Fleet

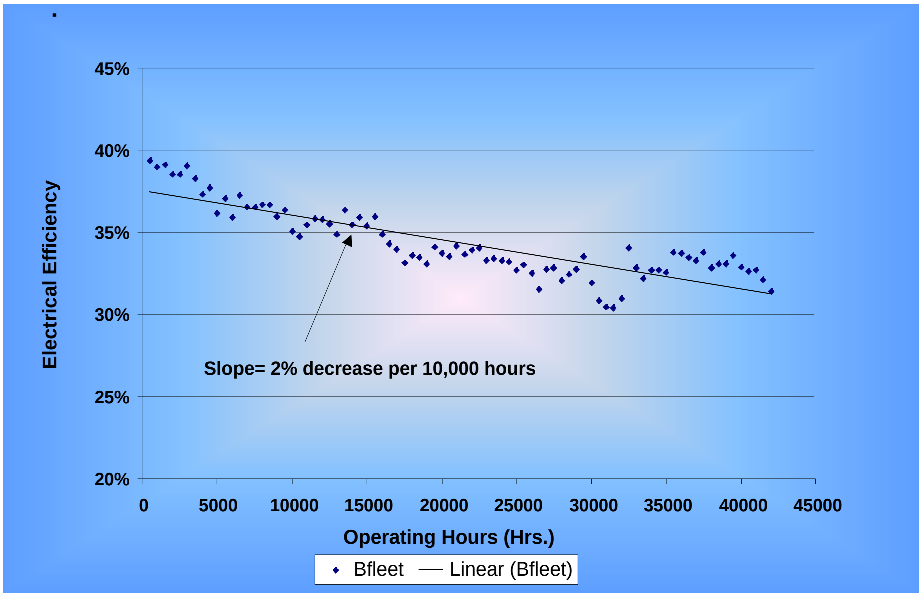

Figure 4. Instantaneous Electrical Output Efficiency – Model PC25B Fleet

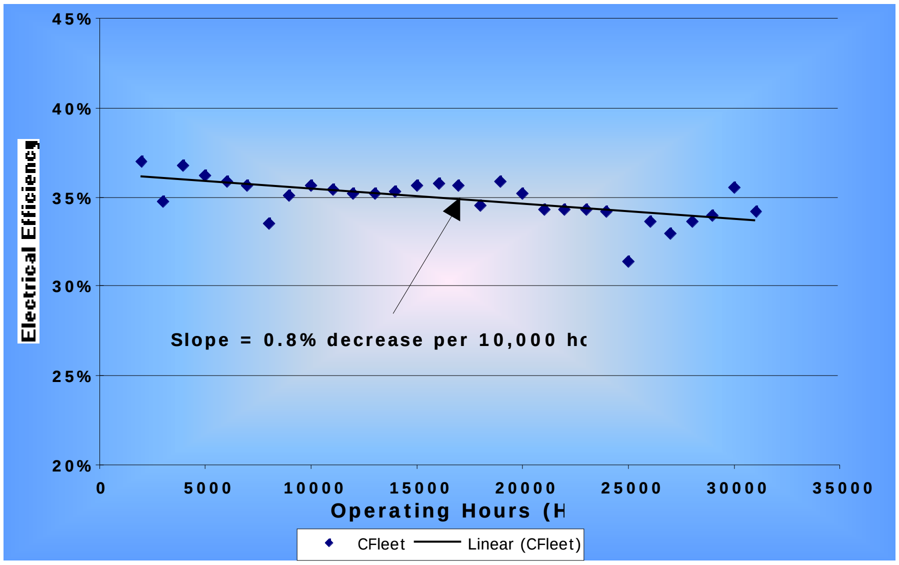

Figure 5. Instantaneous Electrical Output Efficiency – Model PC25C Fleet

Current Operating Status

Two of the Model PC25B power plant sites have had their fuel cells removed. One site has experienced a cell stack failure and has requested that their fuel cell be removed. Another site has determined that it is no longer economically feasible to continue to operate their power plant and therefore has elected to voluntarily shut down their power plant and request its removal. Of the remaining Model PC25B fleet, two are operating at 200 kW, four are operating between 150 and 175 kW, and four are operating at 125 kW.

All of the Model PC25C fleet are currently in operation. One is operating at 200 kW, nine are operating between 150 and 185 kW, four are operating at 125 kW, and one is operating at 80 kW.

Environmental Emissions

Field measurements of environmental air emissions were performed at three of the Model PC25B PAFC power plant sites. Measurements of NO_x, SO_x, CO, and Volatile Organic Compounds (VOCs) were taken twice at each site at six-month intervals, at output power ratings of 100 kW, 150 kW, and 200 kW. SO_x measurements were below detectable limits on each occasion. In all cases, measured values of NO_x, CO, and VOCs were less than the manufacturers published values of 1.0 ppm, 5.0 ppm, and 1.0 ppm, respectively (taken at 15% O_2, dry). This verified that emission estimates based on the manufacturer's specifications would yield conservative results. By estimating emissions from the site-specific mix of conventional electric generation technologies supplying the local grid (and now displaced by fuel cell generation), it has been estimated that the DoD fuel cell fleet has abated 1.79×10^5 kg of NO_x, 3.83×10^5 kg of SO_x, 1.54×10^4 kg of CO, and 2.27×10^7 kg of CO_2. It is planned to make similar measurements on several sites in the Model PC25C fleet in the near future.

SITE MANAGEMENT SYSTEM

In addition to the PAFC Power Plant Demonstration Program discussed above, USAERDC/CERL has also sponsored cost-shared research with ONSI Corporation for cost reduction and product improvements. In particular, the Demonstration Program pointed out two major shortcomings in the capability of the existing ONSI PC25 fuel cell. The first had to do with the fact that multiple fuel cells operating independent of the utility grid could each serve dedicated 200-kW loads, but could not serve an aggregate load greater than 200 kW. There was a need to develop the ability for multiple fuel cells to operate together to share an aggregate load. The other shortcoming had to do with the transition from grid-parallel operation to grid-independent operation in the event of loss of the utility grid. This transition typically took several seconds, far in excess of that required to assure continuity of sensitive, critical electronic loads.

USAERDC/CERL cosponsored with ONSI the development of a Site Management System (SMS) that allows for multi-unit load sharing and seamless transfer capability. The system has been undergoing demonstration at the U.S. Postal Services Main Processing Center in Anchorage, AK since August, 2000. This site was chosen for this demonstration because it experienced frequent momentary outages of the local utility grid. This caused shut down of the mail sorters requiring a two-hour time period to clear and restart them, resulting in considerable lost productivity and time. Concurrently, the Processing Center needed to replace a back-up diesel generator and an inadequate UPS system. The SMS along with five ONSI Model PC25C PAFC power plants were installed by, and are currently operated by, Chugach Electric Association, the local utility company.

Under normal operation, the fuel cells operate in parallel to the utility grid, supplying all power to the Postal facility (~ 800 kW peak), with the excess power provided to the Chugach Electric Association grid. In the event of the loss of utility power, the power plants transfer from the grid-connect to the grid-independent mode of operation seamlessly (less than _ cycle). The five fuel cells share the facility load, thereby replacing the diesel generator set and UPS. When the utility grid is restored, the fuel cells again transition seamlessly back to the grid-connect mode of operation. The by-product heat from the fuel cells is recovered to provide heating to the Postal facility.

This demonstration features a number of project "firsts." It is the first site to ever use five fuel cells operating together in the multi-unit load sharing mode. It is the first fuel cell installation to provide power continuity to the load by means of seamless transfer between the grid-connect and grid-independent modes of operation. It is also the first use of a fuel cell installation as a distributed generation asset by a local electric utility. The Processing Center has not experienced any loss of power to the facility load since the installation of this fuel cell/SMS system.

CONCLUSIONS

The traditional approach toward commercialization by fuel cell developers is to conduct carefully designed, tightly controlled field demonstrations. However, the true test comes when the fuel cells are put into normal everyday operation and expected to perform under those conditions. The intentional diverse nature of the DoD Fuel Cell Demonstration Program served to identify in a very short time period a number of shortcomings associated with the fuel cells operating under certain site specific conditions; for example, altitude, ground water contamination, heat, cold, humidity, etc. In each instance where a shortcoming was identified, it resulted in a manufacturer's retrofit to improve the product. The overall result of the program has been improved product performance that has been observable in the fleet performance data.

Monitoring of the DoD fleet is on-going. Additional information on DoD sites and performance updates are available at the website address: www.dodfuelcell.com.